

X-RAY AND GAMMA-RAY EMISSION FROM

CLASSICAL NOVA OUTBURSTS

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ABSTRACT

The outbursts of classical novae are now recognized to be consequences of thermonuclear runaways proceeding in accreted hydrogen-rich shells on white dwarfs in close binary systems. For the conditions that are known to obtain in these environments, it is expected that soft x-rays can be emitted, and indeed x-rays have been detected from a number of novae. We will describe the circumstances for which we expect novae to produce significant x-ray fluxes and provide estimates of the luminosities and effective temperatures. We now also know that, at the high temperatures that are known to be achieved in this explosive hydrogen-burning environment, significant production of both ^{22}Na and ^{26}Al will occur. In this context, we identify the conditions for which gamma-ray emission may be expected to result from nova outbursts.

I. INTRODUCTION

It is now well established that the outbursts of the classical novae result from thermonuclear runaways in accreted hydrogen shells on white dwarfs in close binary systems (see, e.g. the reviews by Truran 1982; Starrfield 1989; Shara 1989). The temperatures that are typically achieved at the peak of the outburst, 200–300 million degrees Kelvin, drive explosive (hydrogen) burning of the available nuclear fuel and allow the formation of significant abundances of the interesting radioactive nuclei ^{22}Na ($\tau_{1/2} = 2.6$ years) and ^{26}Al ($\tau_{1/2} = 7.2 \times 10^5$ years). It follows that novae in outburst might yield detectible flux levels of decay gamma rays from ^{22}Na and that they may also contribute to the observed level of ^{26}Al decay gamma rays in the Galaxy. During the later stages of the outbursts, the effective temperatures characteristic of the hydrogen burning white dwarf remnants will evolve to values in excess of 200 thousand degrees

Kelvin, as the surface radius retreats with progressive depletion of the residual hydrogen fuel. Photospheric temperatures in this range, together with the fact that nuclear burning on white dwarfs proceeds at luminosities near Eddington, would allow an understanding of the levels of x-ray emission observed by EXOSAT for several novae.

The aim of this paper is to identify and to discuss the characteristics of the outbursts of the classical novae that dictate the expected levels and timescales of x-ray and gamma-ray emission. A brief review of the salient features of the thermonuclear runaway model for classical nova explosions is presented in the next section. The observational situation regarding x-rays and gamma rays from novae is reviewed in section III. Theoretical expectations for x-ray and gamma-ray emission and the possible interpretation of the observed soft x-ray output of classical novae are presented in section IV. Theoretical expectations concerning the detection of ^{22}Na and ^{26}Al gamma ray lines from novae are then discussed in section V. A brief summary and conclusions follow.

II. THE THERMONUCLEAR RUNAWAY MODEL

The outbursts of classical novae are a consequence of thermonuclear runaways occurring in accreted hydrogen shells on white dwarfs. The runaway is generally initiated at or near the base of the accreted envelope, when a critical pressure is achieved. The high temperatures typically achieved in the burning regions, $\sim 1.5\text{--}3 \times 10^8$ K, drive convection, which is efficient in transporting the released nuclear energy to the surface. During the earliest stages of the runaway, the convective burning shell extends outward to encompass the entire envelope. The convective timescale characteristic of nova envelopes is well less than a day. This ensures the realization of a luminosity approaching or exceeding the Eddington limit, $\sim 2\text{--}4 \times 10^4 L_{\odot}$, on a rapid timescale with respect to the timescale of envelope expansion, and therefore of a high effective temperature, $\sim 5 \times 10^5$ K. During this early (pre-maximum) phase, novae are therefore expected to be soft x-ray sources and UV sources.

Convection at this stage also acts to mix the products of thermonuclear burning, in the shell source to the surface. In this instance, substantial quantities of the short-lived positron-unstable products of explosive hydrogen burning, ^{13}N , ^{14}O , ^{15}O , ^{17}F , and ^{18}F , can be transported to the surface. Decay of these radioactive isotopes in the surface regions, occurring in novae prior to the realization of visual maximum, can possibly produce a strong gamma-ray flux (Leising and Clayton 1987). We should also note that these same explosive hydrogen burning conditions can result in the production of significant concentrations of the longer lived radioactivities ^{22}Na and ^{26}Al , as will be discussed further in a later section.

Hydrodynamic studies of nova eruptions predict that, following runaway, and a relatively brief phase of evolution at luminosities that can exceed Eddington (Truran 1982), shell hydrogen burning of the residual matter defines a phase of evolution characterized by a constant bolometric luminosity. During this phase, there occurs a gradual hardening of the spectrum with time, as the photospheric

radius decreases slowly with the depletion of the envelope mass. Classical novae will then become, progressively, first strong ultraviolet sources and then soft x-ray sources. Both the timescale for the realization of the stage of soft x-ray emission, and the timescale for the duration of this stage, are dependent upon the mass of the underlying white dwarf and the efficiency of mass loss mechanisms in depleting the hydrogen envelope mass (MacDonald, Fujimoto, and Truran 1985). It is this stage of soft x-ray emission that, presumably, was detected and identified with EXOSAT for several recent novae (Ogelman, Krautter, and Beuermann 1987). Following the depletion of the envelope fuel and the termination of shell hydrogen burning, the nova white dwarf remnant evolves rapidly to minimum along a path consistent with evolution to lower luminosity at constant radius.

III. OBSERVATIONS OF X-RAYS AND GAMMA RAYS

Observations of classical novae at x-ray wavelengths have been performed to date both with Einstein and with EXOSAT. Einstein detections include V841 Oph 1848, V1059 Sgr 1898, GK Per 1901, V603 Aql 1918, RR Pic 1925, CP Pup 1942, RR Tel 1946, and V1500 Cyg 1975 (Becker 1989; Ogelman 1990). These include novae ranging in speed class from slow to very fast, with no apparent correlation. Of these, only RR Tel 1946 and V1500 Cyg 1975 can be said in any sense to have been observed in outburst; RR Tel is an extremely slow nova, often referred to as a symbiotic nova, which still exhibits a rich ultraviolet spectrum, while V1500 Cyg was observed approximately 1000 days into its outburst.

The EXOSAT detections of x-rays from the three classical novae GQ Mus 1983, PW Vul 1984, and QU Vul 1984 (Ogelman, Krautter, and Beuermann 1987) comprise the most comprehensive study of novae and provide extremely interesting and important constraints on the late evolution of classical novae in outburst. The data for PW Vul and QU Vul both indicate a rise in the x-ray flux occurring on a timescale of less than approximately one year, while the emission from GQ Mus is seen to remain roughly constant over the second year of its outburst, following which it falls on approximately the same timescale. The fact that the rise in the x-ray luminosity occurs so early in the outburst, and ultimately disappears on a timescale of several years, confirms a rapid evolution of novae in outburst consistent with the fact that the mean mass of classical novae observed in outburst is rather high, of order 1.2 solar masses (Truran and Livio 1986, 1989; Ritter et al. 1991). The level of x-ray emission detected is also consistent with the fact that a significant fraction of the nova luminosity appears in the soft x-ray regime (Ogelman, Krautter, and Beuermann 1987).

The observational situation with regard to gamma rays from classical novae may be summarized very rapidly. ^{22}Na decay gamma rays have not yet been detected from any nova in outburst, although we now expect that such detection may be possible with GRO. Alternatively, gamma rays from ^{26}Al decay have been detected (Mahoney et al. 1982, 1984), but the nucleosynthesis site for ^{26}Al production has not been clearly identified. These issues will be discussed further in section V.

IV. THEORETICAL EXPECTATIONS FOR X-RAYS AND GAMMA RAYS

X-rays

The evolution of a nova through its outburst that we have outlined above reveals that novae may be expected to be sources of soft x-ray (and EUV) emission in two distinct phases. Soft x-ray emission arises here when photospheric effective temperatures typically exceeding approximately 200,000 K are achieved in hydrogen shell burning at near Eddington luminosities. A brief early phase (occurring prior to maximum) and an extended late phase of such x-ray emission are expected.

The early phase of emission is associated with the early dynamic phase prior to the achievement of visual maximum. When the convective region driven by the thermonuclear runaway in the shell source first reaches the surface, the high luminosity (near to or even exceeding the Eddington limit) and small radius (of order 10^9 cm) imply a photospheric temperature of some hundreds of thousands of degrees. Indeed, for a white dwarf of mass approaching the Chandrasekhar limit, a photospheric temperature exceeding a million degrees is expected.

Unfortunately, this phase of evolution is found to be of extremely short duration. The large energy deposition into the nova envelope by convection triggers a rapid expansion of the envelope, an increase in the radius of the photosphere, and a concomitant decrease in T_{eff} . A typical expansion velocity of $10^7 - 10^8$ cm s⁻¹, for example, would yield a radius in excess of 10^{11} cm on a timescale of less than a day; at this radius, T_{eff} has fallen below 100,000K and significant soft x-ray emission does not occur. Such an event, if detectable by a sensitive all sky survey, would appear as a very soft x-ray transient.

The second and more extended period of soft x-ray and EUV emission occurs subsequent to visual maximum, when all novae are found to experience a phase of evolution at constant bolometric luminosity associated with hydrogen shell burning at near Eddington luminosities. The timescale of this phase is a function of the timescale for the depletion of the residual envelope hydrogen by some yet undetermined combination of nuclear burning, wind-driven mass loss, and common-envelope driven mass loss (see, e.g. the discussion by MacDonald, Fujimoto, and Truran (1985)). As the envelope mass is depleted, the photospheric radius decreases and consequently the photospheric temperature rises; this ultimately gives rise to a hardening of the radiation to UV, EUV, and soft x-ray wavelengths. Theoretical estimates of the time required to reach temperatures consistent with x-ray emission are very uncertain. It is therefore necessary to rely on observations to determine this timescale and thereby impose critical constraints on theoretical models. The x-ray observations of several recent novae with EXOSAT (Ögelman, Krautter, and Beuermann 1987), now seem to have identified this second phase of soft x-ray emission from classical novae.

Gamma rays

Considerations of gamma-ray emission from classical novae are primarily concerned with gamma-ray line emission from the radioactive nuclei ^{22}Na (2.6

years) and ^{26}Al (7.2×10^5 years), which are known to be formed under the high temperature hydrogen burning conditions associated particularly with the peak of the thermonuclear runaway. Clayton and Hoyle (1974) first noted that individual novae might produce detectible flux levels of ^{22}Na decay gamma rays, and recent calculations (Weiss and Truran 1990; Politano, Starrfield, Truran, Sparks, and Weiss 1991) provide estimates of ^{22}Na production at levels sufficient to allow the detection of gamma rays from nearby novae. Significant ^{26}Al production can also be expected to occur, but it currently appears unlikely that ^{26}Al produced in novae can have contributed significantly to the flux of ^{26}Al decay gamma rays detected by Mahoney *et al.* (1982,1984). These issues will be discussed at greater length in section V.

We also note, again, that there exists the possibility of an early phase of gamma-ray emission from novae in outburst, driven by the decay of the short lived radioactivities ^{13}N , ^{14}O , ^{15}O , ^{17}F , and ^{18}F in the outermost regions of the nova envelope (Leising and Clayton 1987). A further investigation of this problem is now in progress, based upon an improved treatment of the thermonuclear reaction sequences leading to the production of these isotopes.

V. ^{22}Na and ^{26}Al DECAY GAMMA RAY LINES

Several recent papers have addressed the question of ^{22}Na and ^{26}Al production in classical nova explosions. Weiss and Truran (1990) and Nofar, Shaviv, and Starrfield (1991) have calculated nucleosynthesis accompanying nova explosions for representative temperature histories extracted from hydrodynamic models. These studies confirmed the findings of earlier work (Hillebrandt and Thielemann 1982; Wiescher *et al.* 1986) that only relatively low levels of ^{22}Na and ^{26}Al are formed in nova envelopes of initial solar composition and revealed, alternatively, that significantly increased ^{22}Na and ^{26}Al production can occur in envelope matter characterized by large initial concentrations of elements in the range from neon to aluminum.

The significance of this latter finding arises from the fact that the ejecta of a significant fraction of well studied novae are found to be enriched in nuclei in the Ne-Al region (see e.g. the review by Truran 1990). Since the source of these large abundance enrichments is assumed to be matter dredged up from the underlying white dwarf, this is taken to reflect the fact that such systems involve massive oxygen-neon-magnesium (ONeMg) white dwarfs, rather than CO white dwarfs. It is understood that the relatively large observed number of such massive systems is a natural consequence of selection effects (Truran and Livio 1986): more massive white dwarfs require less accreted matter (hence shorter accretion phase timescales) to achieve runaway conditions. Indeed, a more careful analysis by Ritter *et al.* (1991) now indicates that a fraction 0.32–0.65 of all systems observed in outburst may be expected to involve ONeMg white dwarfs.

Specific estimates of ^{22}Na and ^{26}Al synthesis are provided by the calculations of Weiss and Truran (1990). They obtain ^{22}Na mass fractions as high as 10^{-4} , for an assumed ONeMg enrichment at a level 0.25 by mass of the ejecta, and values

exceeding 10^{-3} when the ONeMg mass fraction is taken to be 0.75. The corresponding concentrations achieved for ^{26}Al for the same two levels of ONeMg enrichment are 10^{-3} and 10^{-4} , respectively. These high levels of production of ^{22}Na and ^{26}Al associated with the ONeMg enrichment of nova envelopes have now been confirmed by detailed studies of nova nucleosynthesis performed with large nuclear reaction networks coupled directly to the hydrodynamics (Politano *et al.* 1991). We now briefly consider the implications of these findings for observational studies with the Compton Gamma Ray Observatory.

The principal question of interest regarding ^{26}Al is whether novae can have contributed significantly to the production of the $3 M_{\odot}$ of ^{26}Al in the Galaxy that is required to explain the 1.809 MeV gamma ray line emissions reported by Mahoney *et al.* (1982, 1984). The mass of ^{26}Al in the Galaxy that is attributable to nova explosions can be estimated from the following expression (Weiss and Truran 1990):

$$M_{26} = 0.4 M_{\odot} \left(\frac{R_{\text{nova}}}{40 \text{ yr}^{-1}} \right) \left(\frac{f_{26}}{0.25} \right) \left(\frac{M_{\text{ej}}}{2 \times 10^{-5} M_{\odot}} \right) \left(\frac{X_{26}}{2 \times 10^{-3}} \right)$$

Here, we have assumed a rate of occurrence of nova events of 40 yr^{-1} , a fraction 0.25 of all nova events that produce ^{26}Al , an ejected mass of $2 \times 10^{-5} M_{\odot}$ per event, for these more massive systems, and a ^{26}Al mass fraction in the ejecta of 2×10^{-3} . This result clearly falls short of the approximately $3 M_{\odot}$ required to account for the gamma ray observations. It would thus appear that some other source, e.g. supernovae or, more likely, red giant stars, must be the dominant source. Information concerning specifically the distribution of ^{26}Al in the Galaxy may ultimately be able to distinguish between these possible sources.

The high levels of ^{22}Na that our calculations indicate may characterize the ejecta of ONeMg enriched novae, allowing the exciting possibility that such novae can produce detectable flux levels of 1.275 MeV gamma rays from ^{22}Na decay. The predicted flux is given by

$$F_{1.275} = 1.6 \times 10^{-4} \text{ cm}^{-2} \text{ sec}^{-1} \left(\frac{e^{-t/3.75}}{(D/500 \text{ pc})^2} \right) \left(\frac{M_{\text{ej}}}{10^{-4} M_{\odot}} \right) \left(\frac{X_{22}}{10^{-4}} \right)$$

where M_{ej} is the total mass of nova ejecta and X_{22} is the mass fraction of ^{22}Na in the ejecta. The specific choices of $X_{22} = 2 \times 10^{-4}$ and $M_{\text{ej}} = 2 \times 10^{-5}$ correspond to reasonable (but not extreme) estimates, for the ONeMg enriched novae in which the ^{22}Na is most likely to be synthesized in significant quantities.

The strategy with regard to searches for 1.275 MeV ^{22}Na decay gamma rays from novae thus seems clear. If one knows from early observations both that a nova is at a distance less than approximately one kiloparsec and that its

envelope is significantly enriched in neon and magnesium, it follows that it constitutes a more promising target. We also call attention to the fact that the radioactive decay of ^{22}Na may play an interesting role in the production of hard x-rays, particularly in novae enriched in oxygen, neon, and magnesium (Livio *et al.* 1991).

VI. CONCLUSIONS

Conclusions to be drawn from these considerations of classical nova outbursts include the following.

1) Significant x-ray and gamma-ray emission is expected to accompany the outbursts of classical novae. X-rays have been observed, while gamma rays have not been detected to date.

2) Soft x-ray emission is expected to be associated with nova outbursts, as effective photospheric temperatures exceeding 300,000 K will be achieved in the presence of shell hydrogen burning at luminosities approaching Eddington on the white dwarf. A brief period of x-ray emission may occur early, prior to optical maximum. A more extended phase of x-ray emission is expected to occur in the late stages of evolution at constant bolometric luminosity, as the white dwarf surface retreats with the exhaustion of the envelope matter.

3) The observed features of this late phase of x-ray emission – an increase on a timescale of 300–500 days, to a plateau which lasts approximately 300–500 days, followed by a decay (Ögelman *et al.* 1987) – have been interpreted by Truran and Livio (1991) as due to an early epoch of rapid (common envelope driven) mass loss followed by a phase of nuclear burning through fuel exhaustion.

4) The hot hydrogen burning conditions achieved at the peak of the thermonuclear flashes in novae are consistent with the synthesis of concentrations of both ^{22}Na and ^{26}Al . The levels of production of these isotopes are sensitive functions of both the peak temperature achieved and the level of enrichment of heavy elements in oxygen, neon, and magnesium.

5) The observed level of ^{26}Al in the Galaxy is unlikely to have arisen from classical novae. We estimate that only perhaps 10 percent of the observed ^{26}Al can have been synthesized in this environment.

6) Our estimates of ^{22}Na and ^{26}Al emission are strongly dependent upon the strength and extent of convective mixing during the course of the nova outburst. The detection of ^{22}Na gamma rays from novae could therefore provide interesting constraints on the convective history of the nova envelope and on our theoretical modeling of convective mixing.

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